Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 61 (2014) 2062 – 2065

Energy Procedia

The 6th International Conference on Applied Energy – ICAE2014

On the natural convection enhancement of heat transfer during phase transition processes of solid-liquid phase change materials (PCMs)

Xiaoqin Sun[1,2], Quan Zhang[1], Mario A. Medina[2,*], Kyoung Ok Lee[2]

[1]*College of Civil Engineering, Hunan University, Changsha, 410082, China*

[2] *Dept. of Civil, Env. & Arch. Engineering, University of Kansas, Lawrence, 66045, USA*

Abstract

Natural Convection is a major factor that affects phase transition processes of solid-liquid phase change materials (PCMs). To optimize PCM-based latent thermal energy storage systems (TESS), a better understanding of the heat transfer during these transitions is critical. This paper presents an experimental approach used to quantify heat transfer rate increase by natural convection of PCMs undergoing phase transitions. For this a heat transfer enhancement factor and an effective heat transfer coefficient were developed. Mean heat transfer enhancement factors of 1.11 and 1.30 were observed and attributed to natural convection during phase transition for vertical and horizontal heat transfer directions, respectively. Natural convection reduced the time required for absorbing the latent heat during melting processes by a mean value of approximately 47%.

Peer-review under responsibility of the Organizing Committee of ICAE2014

Keywords: Natural convection, phase change materials (PCMs), phase transition, energy storage.

1 Introduction

Thermal energy storage systems (TESS) are used for regulating the time-of-use mismatch between energy generation and consumption [1]. Among TESS, which include sensible energy storage [2], latent energy storage [3], and chemical energy storage [4], latent energy storage systems that use phase change materials (PCMs) are particularly attractive because PCMs provide a high energy storage density and approximate isothermal phase transitions. Energy is stored in phase changing substances when these melt. This energy is recovered following solidification. Because natural convection in molten PCMs enhances the heat transfer within these systems, a better understanding of the substances used as PCMs as well as the physical phenomena that take place during phase transition is needed. These include, but are not limited to, PCM thermal characteristics and heat transfer process interactions during phase transitions [5].

* Corresponding author. Tel.: +1 785 864 3604. Fax: +1 785 864 5631. E-mail address: mmedina@ku.edu (**Mario A. Medina**)

Peer-review under responsibility of the Organizing Committee of ICAE2014
doi:10.1016/j.egypro.2014.12.076

Baran et al. [6] concluded that melting and solidification of PCMs were highly influenced by natural convection (in the case of melting) and by conduction (in the case of solidification). Longeon et al. [7] concluded that natural convection enhanced the melting processes of PCMs, while Duan et al. [8] found that buoyancy effects within molten PCMs increased the heat transfer rate to and from the PCMs.

In summary, there is a close relationship between natural convection in molten PCMs and the enhancement of heat transfer to and from the PCM during phase transition, especially during the melting process. This paper presents an experimental approach used to quantify this enhancement via the development of a heat transfer enhancement factor and an effective heat transfer coefficient.

2 Experiment apparatus

The PCM used for these tests was an octadecane paraffin. Its thermal properties are provided in Table 1.

Table 1 PCM thermal property data [9]

Type	Approximate melting point [°C]	Approximate solidification point [°C]	Latent heat of fusion [kJ/kg]	Density [kg/m^3] solid	Density [kg/m^3] liquid	Conductivity [W/(m°C)]
Paraffin	28	26	147	870	750	0.2

An environmental simulator (Fig. 1a) was fabricated to provide various ambient air temperatures. The simulator was located in an air-conditioned laboratory where the air temperature was kept at approximately 22~24^{o}C. The PCM was placed inside a cubic aluminum container with dimensions of 20 cm on each side. To restrict the heat flow to and from the container, this was heavily insulated with foam with a thermal resistance of 8.63 m^{2o}C/W. To monitor the ambient air temperatures outside the aluminum container, several thermocouples (T/Cs) were installed in various locations within the simulator. To measure the temperature distribution within the PCM, twenty Type T T/Cs were placed inside the container using a structural frame. These T/Cs were arranged in seven layers, from top to bottom (Figs. 1b~1d). Each outer surface temperature of the container as well as each surface temperature of the insulation was measured using four and two T/Cs, respectively. Six heat flux meters (HFMs) were attached to the insulation outer surfaces.

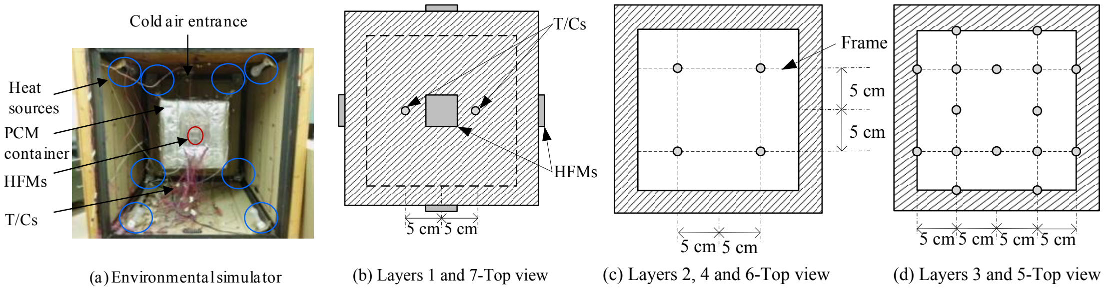

Fig.1 Environmental simulator and the positions of T/Cs and HFMs

3 Results and discussion

Twelve experiments were performed at a fixed ambient air temperature which varied between 5 ^{o}C and 65 ^{o}C. It was pre-established that when all PCM temperatures had surpassed the PCM's melting point, the melting process was complete. After the melting process was completed, the solidification period was initiated. An adjusted Biot number, Bi′, was defined as the ratio of the internal thermal resistance of the PCM to its external thermal resistance. In equation form

$$Bi' = \frac{R_{PCM}}{R_{ext}} = \begin{cases} >1 & \text{PCM thermal resistance dominated} \\ =1 & \text{Neither thermal resistance dominated} \\ <1 & \text{External thermal resistance dominated} \end{cases} \quad (1)$$

The external thermal resistance represented the ambient air thermal resistance (m^2K)/W. *Rayleigh number*, *Ra*, was used to study the effects of natural convection in the liquid PCM. In equation form

$$Ra = \frac{g\beta(T_{air} - T_{PCM})l^3}{\nu\alpha} \tag{2}$$

where g was the gravitational acceleration, m/s^2; β was the coefficient of volume expansion, $1/{}^oC$; T_{PCM} was the mean PCM temperature, ^oC; l was the characteristic length of the PCM container, m; ν was the PCM kinematic viscosity, m^2/s, and α was the PCM thermal diffusivity, m^2/s. All the PCM thermophysical parameters were from Refs. 9 and 10.

Fig.2 shows the Bi' as a function of Ra. Because Bi' was less than 1, it was inferred that the external thermal resistance dominated during the heat transfer process. The heat transfer enhancement caused by natural convection was evaluated by means of *a heat transfer enhancement factor, f.* This factor was defined as the ratio of the heat transfer coefficient with natural convection to that without natural convection under the same conditions. In equation form

$$f = {\phi_{nc}}/{\phi} = {R}/{R_{nc}} \tag{3}$$

where ϕ was the heat transfer coefficient in W/($m^{2o}C$) and R was the thermal resistance in ($m^{2o}C$)/W. The parameter with the subscript "*nc*" included the effects of natural convection. For energy storage processes, it was found that Bi' decreased with increasing Ra. This was caused by buoyancy forces that developed during the phase transition, which indicated that phase transition from solid to liquid promoted natural convection. During the melting processes, thermal resistances were smaller when the heat transfer was in the horizontal direction than in the case when the heat transfer was in the vertical direction. This indicated that natural convection was more influential in promoting the heat transfer in the horizontal direction [11]. During the solidification processes, it was found that natural convection did not play a significant role. In this case, the observed decrease in Bi' was caused by an increase in the thermal conductivity of the PCM. The mean values of the enhancement factor in the vertical and horizontal heat transfer directions were 1.11 and 1.30, respectively.

Fig. 3 shows the heat fluxes during phase transition. In all cases the heat flux increased with increasing Ra. This was caused by either the increase of buoyancy forces or the decrease of the thermal resistance within the PCM. The highest value of heat flux appeared in the heat storage process in the horizontal heat transfer direction, followed by the heat storage process in the vertical heat transfer direction. The heat fluxes were calculated by

$$q = \frac{Ra}{1+Bi'} \cdot \frac{\nu\alpha}{g\beta l^3} = \frac{Nu\lambda_{cond}}{l} \cdot \left(T_{surface} - T_{PCM}\right) = \begin{cases} \phi\left(T_{surface} - T_{PCM}\right) & \text{For solidification process} \\ \phi_{nc}\left(T_{surface} - T_{PCM}\right) & \text{For melting process} \end{cases} \tag{4}$$

where $\phi_{nc} = Nu\lambda_{cond}/l$ (5)

The PCM thermal conductivity was given by λ_{cond}. When $Nu = 1$, $\phi_{nc} = \phi$, which meant that heat conduction dominated the heat transfer. Fig. 4 shows the phase transition times for melting and solidification for the vertical and horizontal heat transfer directions. It was observed that the time required for complete melting was shorter than for complete solidification. For example, for the vertical heat transfer under the same conditions (A and B), the time required for absorbing latent heat was 34.1 hr, while the time required for releasing the heat was 62.1 hr. The reason for this was the increase of natural convection. The same was true for horizontal heat transfer under the same conditions (C and D). Curve D represented the horizontal heat transfer during melting for a temperature range of 26 ~ 28 ^oC, which was the same temperature range for solidification. The solid line represented the same melting process, but for a wider melting range of 24 ~ 32 ^oC, which was the actual measured range. From the data at points C and D, the phase transition time was reduced by 43% from 22.8 hr, which also indicated the presence of natural convection.

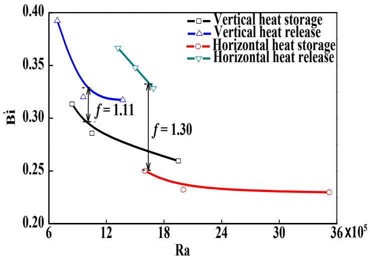

Fig.2 Bi′ vs. Rayleigh number

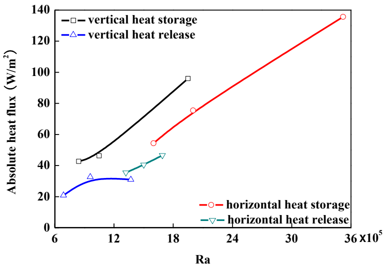

Fig.3 Heat flux vs. Rayleigh number

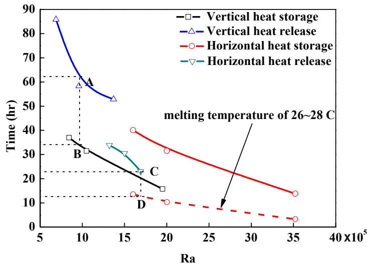

Fig.4 Phase transition time vs. *Ra*

4 Conclusions

This paper presented an experimental approach used to quantify heat transfer rate increase by natural convection of PCMs undergoing phase transitions. A heat transfer enhancement factor and an effective heat transfer coefficient were developed. Mean heat transfer enhancement factors of 1.11 and 1.30 were observed and attributed to natural convection during phase transitions for vertical and horizontal heat transfer directions, respectively. In addition, natural convection reduced the time required for absorbing the latent heat during the melting process for both vertical and horizontal heat transfer processes by a mean value of approximately 47%.

Biography

Xiaoqin Sun is a PhD Candidate at Hunan University. She was a visiting scholar at the University of Kansas. For more information, please contact her at: hnsunxiaoqin@163.com

Acknowledgements

This work was supported by the University of Kansas, National 863 Project (2012AA052503), Hunan Province Projects [2012] No.155 and 2013WK2001.

References

[1] Sun X, Zhang Q, Medina M, Liu Y, Liao S. A study on the use of phase change materials (PCMs) in combination with a natural cold source for space cooling in telecommunications base stations (TBSs) in China. Applied Energy 2014, 117: 95-103.
[2] Miró L, Navarro M, Suresh P, Gil A, Fernández A, Cabeza L. Experimental characterization of a solid industrial by-product as material for high temperature sensible thermal energy storage (TES). Applied Energy 2014, 113: 1261-8.
[3] Casano G, Piva S. Experimental and numerical investigation of the steady periodic solid-liquid phase-change heat transfer. International Journal of Heat and Mass Transfer 2002, 45(20): 4181-90.
[4] Shao H, Nagel T, Roßkopf C, Linder M, Wörner A, Kolditz O. Non-equilibrium thermo-chemical heat storage in porous media: Part 2-A 1D computational model for a calcium hydroxide reaction system. Energy 2013, 60: 271-82.
[5] Sharma A, Tyagi V, Chen C, Buddhi D. Review on thermal energy storage with phase change materials and applications. Renewable and Sustainable Energy Reviews 2009, 13(2): 318-45.
[6] Baran G, Sari A. Phase change and heat transfer characteristics of a eutectic mixture of palmitic and stearic acids as PCM in a latent heat storage system. Energy Conversion and Management 2003, 44(20): 3227-46.
[7] Longeon M, Soupart A, Fourmigué J, Bruch A, Marty P. Experimental and numerical study of annular PCM storage in the presence of natural convection. Applied Energy 2013, 112: 175-84.
[8] Duan X, Naterer G. Heat transfer in phase change materials for thermal management of electric vehicle battery modules. International Journal of Heat and Mass Transfer 2010, 53(23-24): 5176-82.
[9] Yuan F. *A comprehensive study of phase change materials (PCMs) for building walls applications*. University of Kansas, 2009.
[10] Ho C. *Solid-liquid phase change heat transfer in enclosures*. Purdue University, 1982
[11] Çengel Y, Ghajar A. *Heat and mass transfer: Fundamentals and Applications, Fourth Edition*. New York: McGraw-Hill; 2009.